

# Analysis of Fuel Cell Vehicle Hybridization and Implications for Energy Storage Devices



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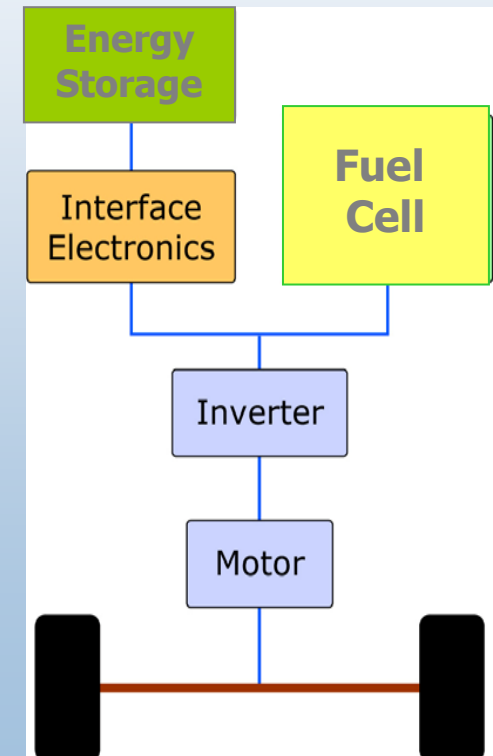
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# Previous Studies

- Hybridization of a fuel cell vehicle with energy storage improves fuel economy, performance and make it practical (UCD, VTech, ANL, NREL)
  - Capturing regenerative braking
  - Improving transient response
  - Smaller fuel cell - lower cost
  - Fuel cell or reformer warm up
- Some demonstration prototype fuel cell vehicles are hybrids
  - Toyota FCHV, Ford Focus– (batteries)
  - Honda FCXV4 – (ultracapacitors)



# Content

- Objectives
- Motivation for using energy storage (ES) in fuel cell (FC) vehicles
- Analyses
- Summary

# Objectives

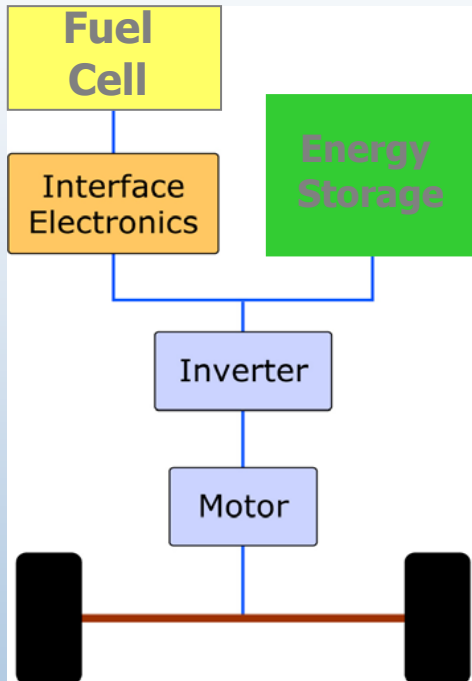
- Investigate the degree of hybridization benefit from:
  - (A) Fuel cell efficiency characteristics
  - (B) Fuel cell downsizing
  - (C) Displacing fuel cell tasks with the ES functionality
  - (D) Energy recovery through regenerative braking

# Motivation for this Study

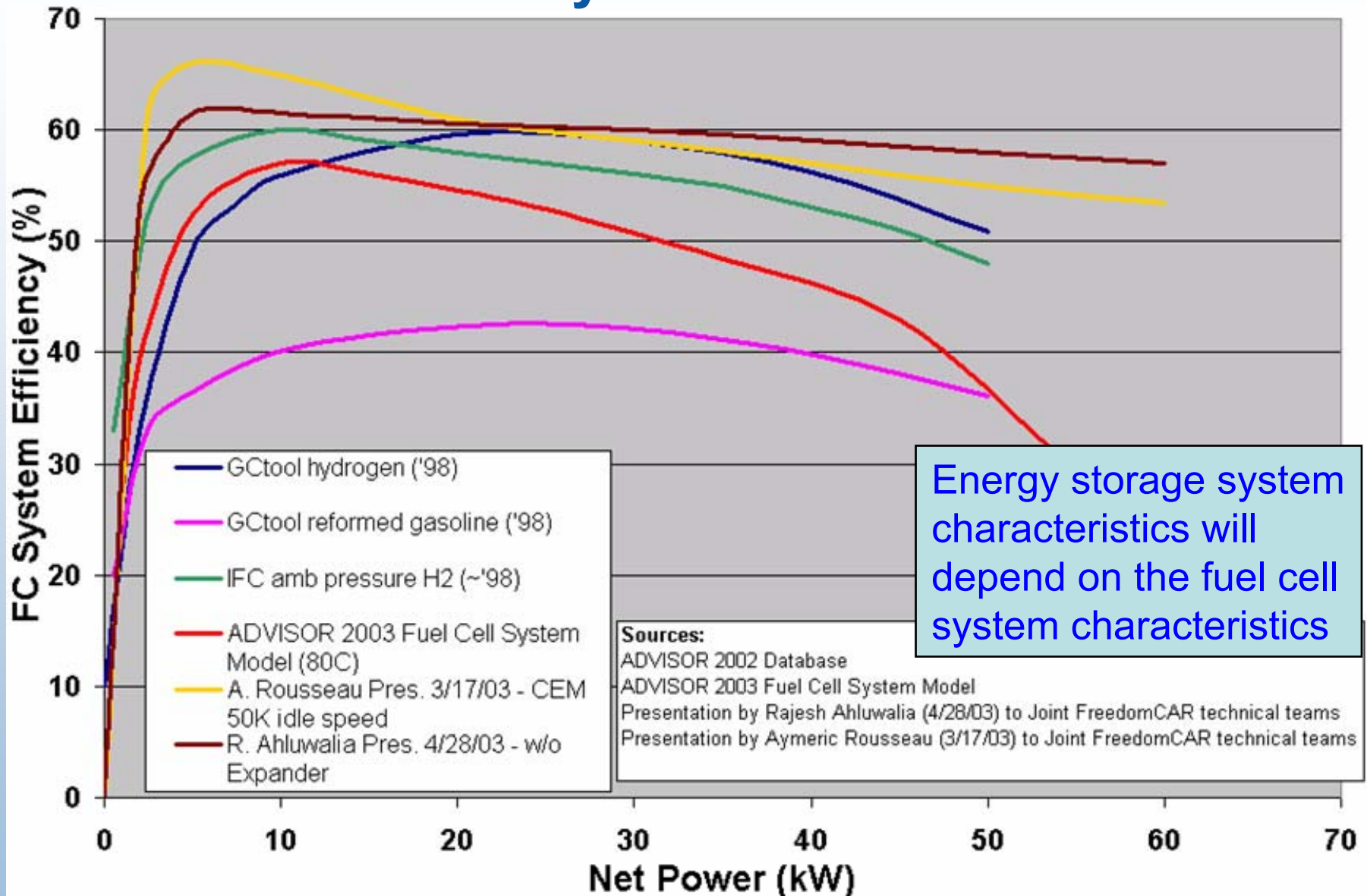
- Previous studies have not separated the degree of hybridization benefits from:

- (a) fuel cell efficiency characteristics,
- (b) fuel cell downsizing,
- (c) displacing fuel cell tasks with the ES functionality
- (d) energy recovery through regenerative braking

- Supporting FreedomCAR in identifying requirements of energy storage for hybrid fuel cell vehicles



# Fuel Cell System Efficiency Variability Could Affect FC-ES Hybridization Outcome



# Fuel Cell and Hydrogen Storage System Assumptions



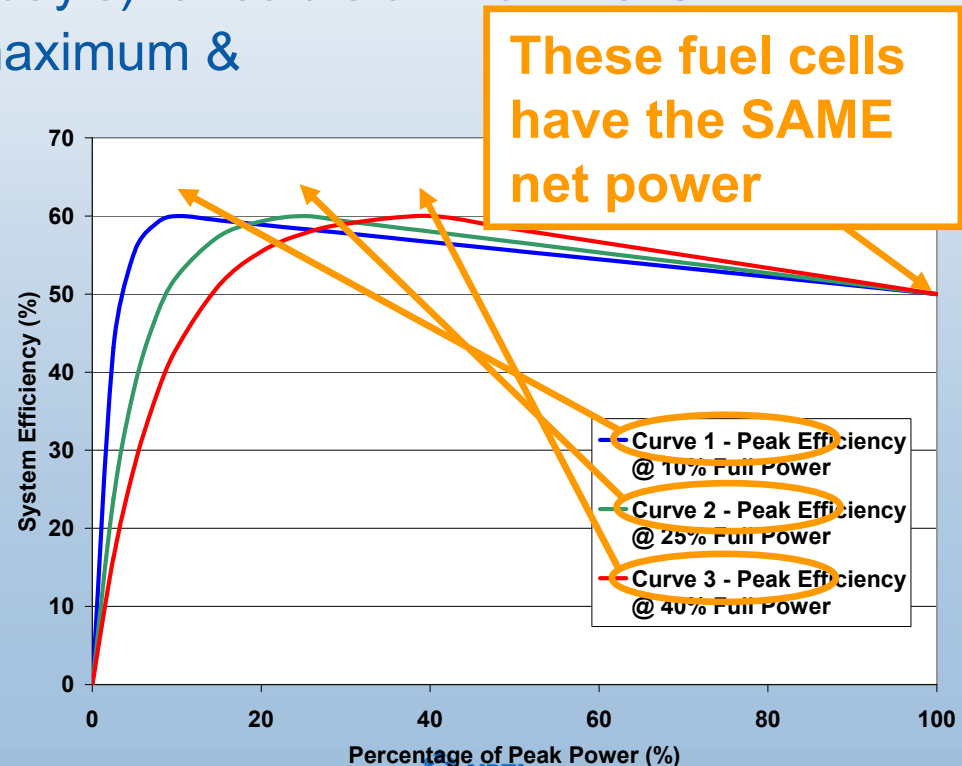
- Fuel Cell

- Sized to provide at least grade performance.
- 1 s or 3 s transient response time (10% to 90% power).
- Reaches maximum rated power in 0 s (ideal case), 15 s (2010 target), or 60 s (today's) for cold start from 20°C.
- System efficiency of 60% at maximum & 50% at rated peak power (DOE Technical Targets).

- Hydrogen Storage

- Pure compressed hydrogen.

Proposed theoretical FC efficiency curves are based on DOE Targets

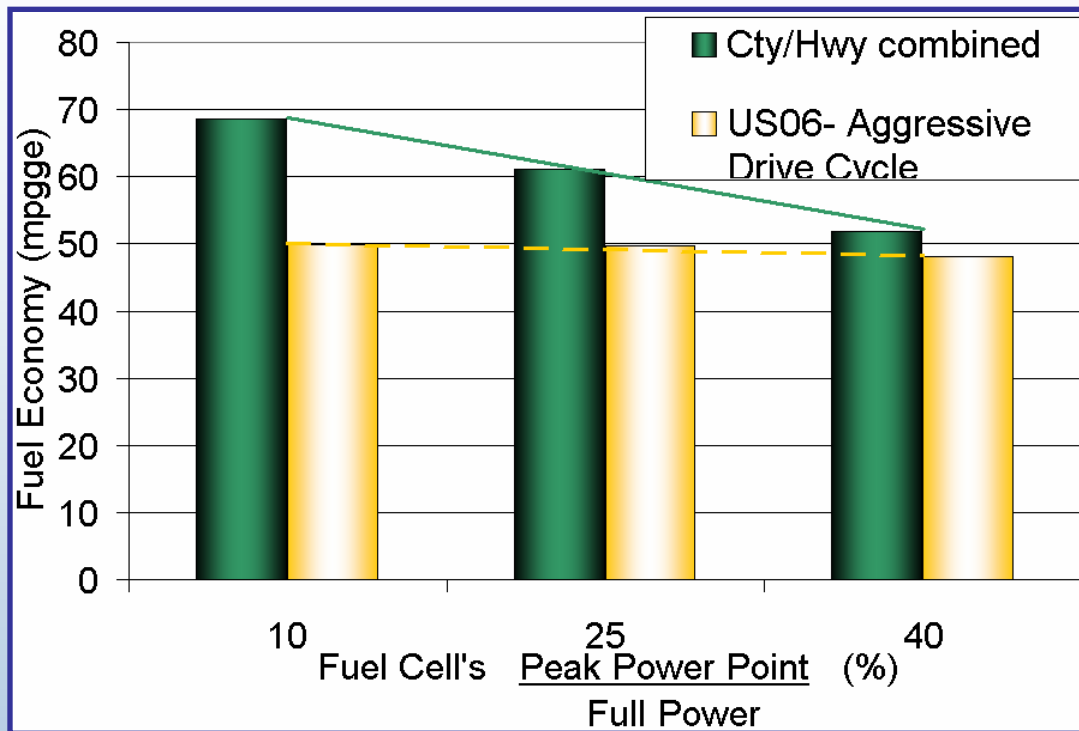




# Objectives

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  - (A) Fuel cell efficiency characteristics**
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# Fuel Economy is Affected by the Position of FC Peak Efficiency

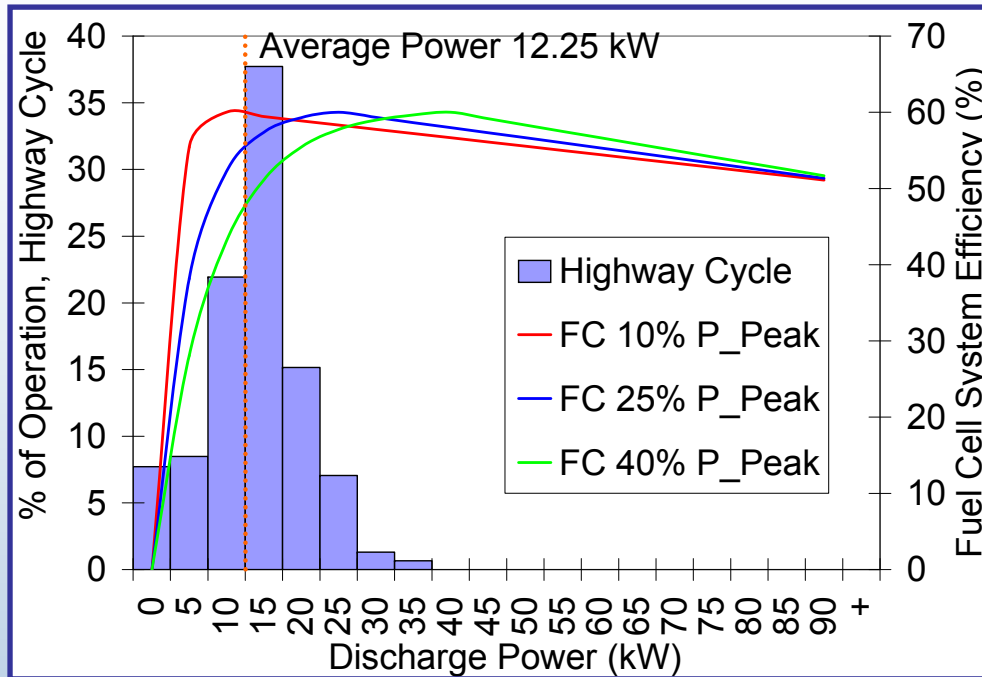


- 10% peak efficiency FC achieved the best city/highway fuel economy

+12% improvement over the 25% peak efficiency configuration

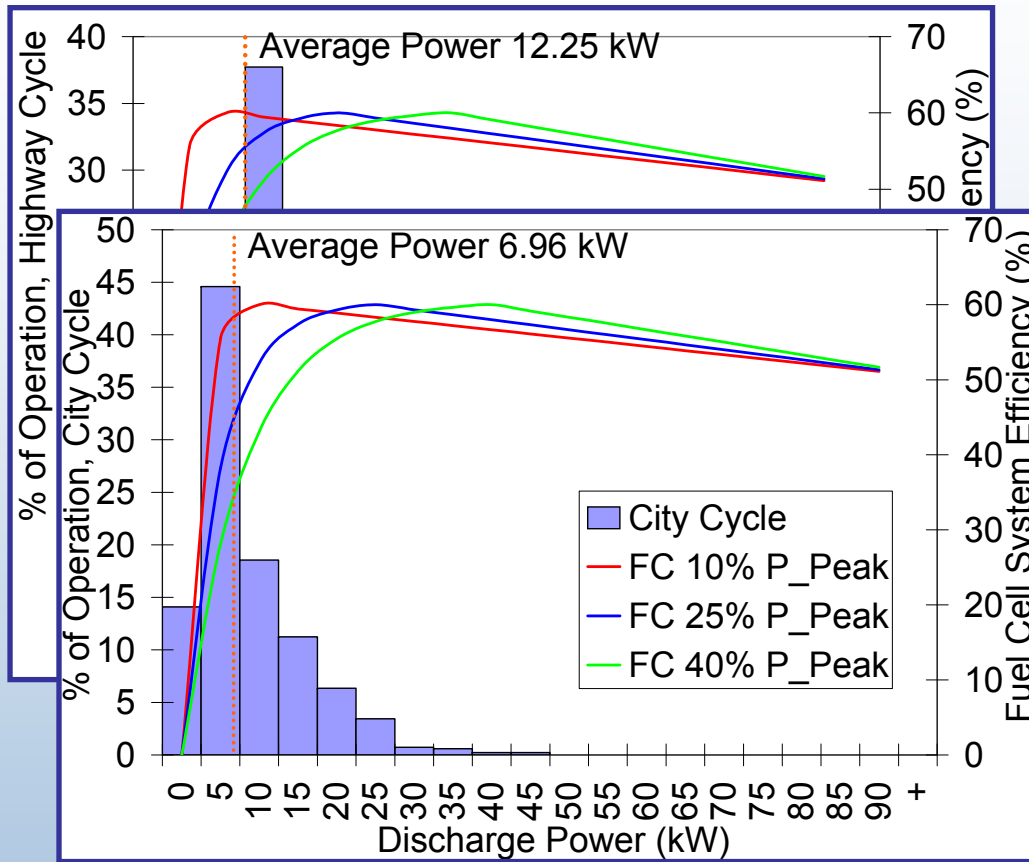
+32% improvement over the 40% peak efficiency configuration

# When Peak Efficiency $\cong$ Typical Power Point, Results in the Best Fuel Economy



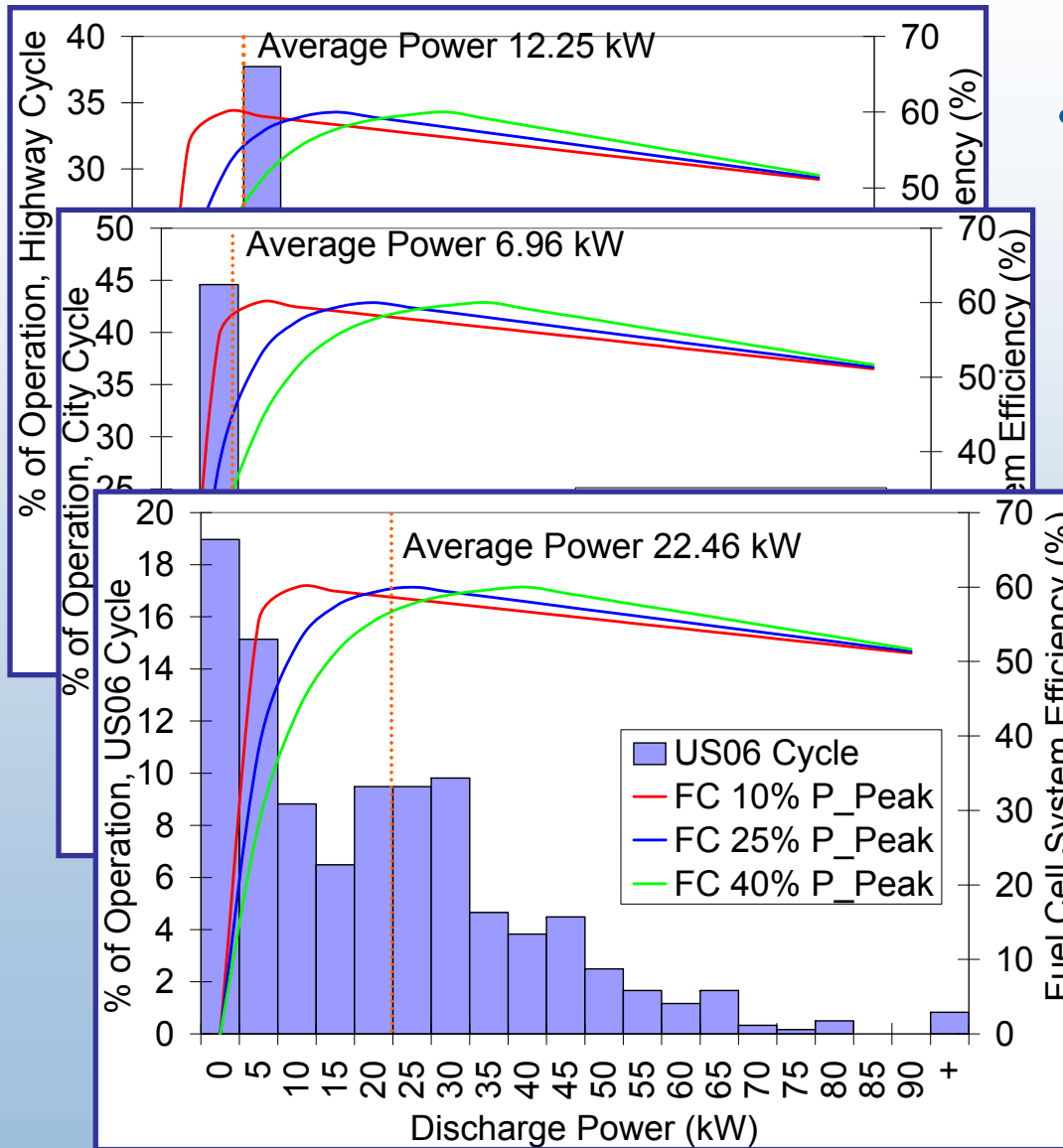
- 10% peak efficiency FC has the highest fuel economy because its peak efficiency is better aligned with the power requirements.

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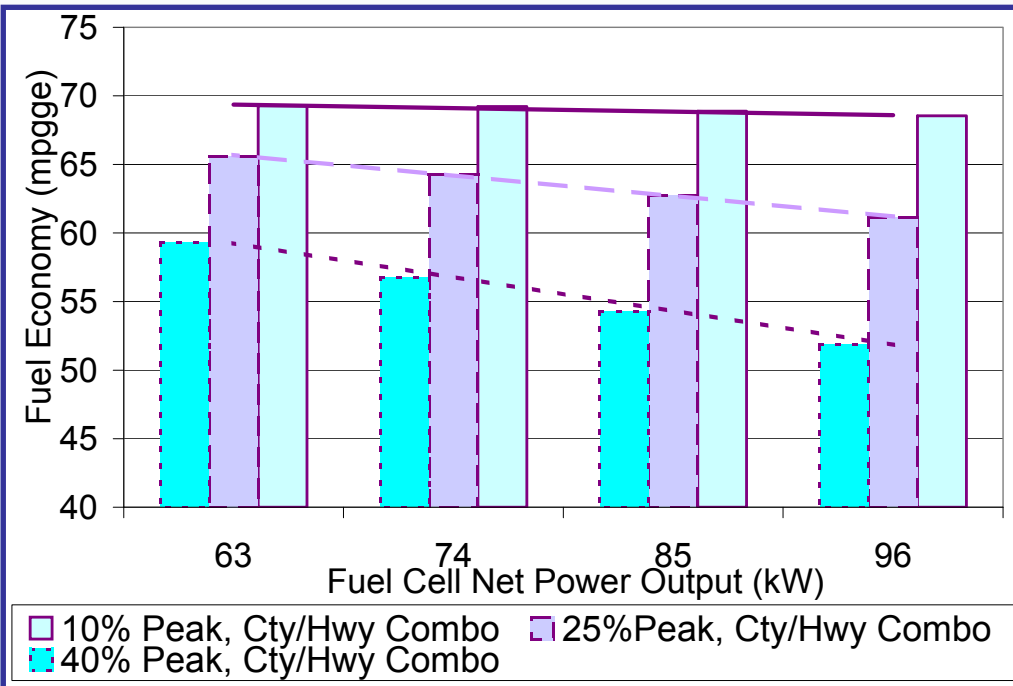


- 10% peak efficiency FC has the highest fuel economy because its peak efficiency is better aligned with the power requirements.
- Little fuel economy difference over US06 cycle.
  - wider power distribution
  - similar efficiency at  $P_{avg}$

# Objectives

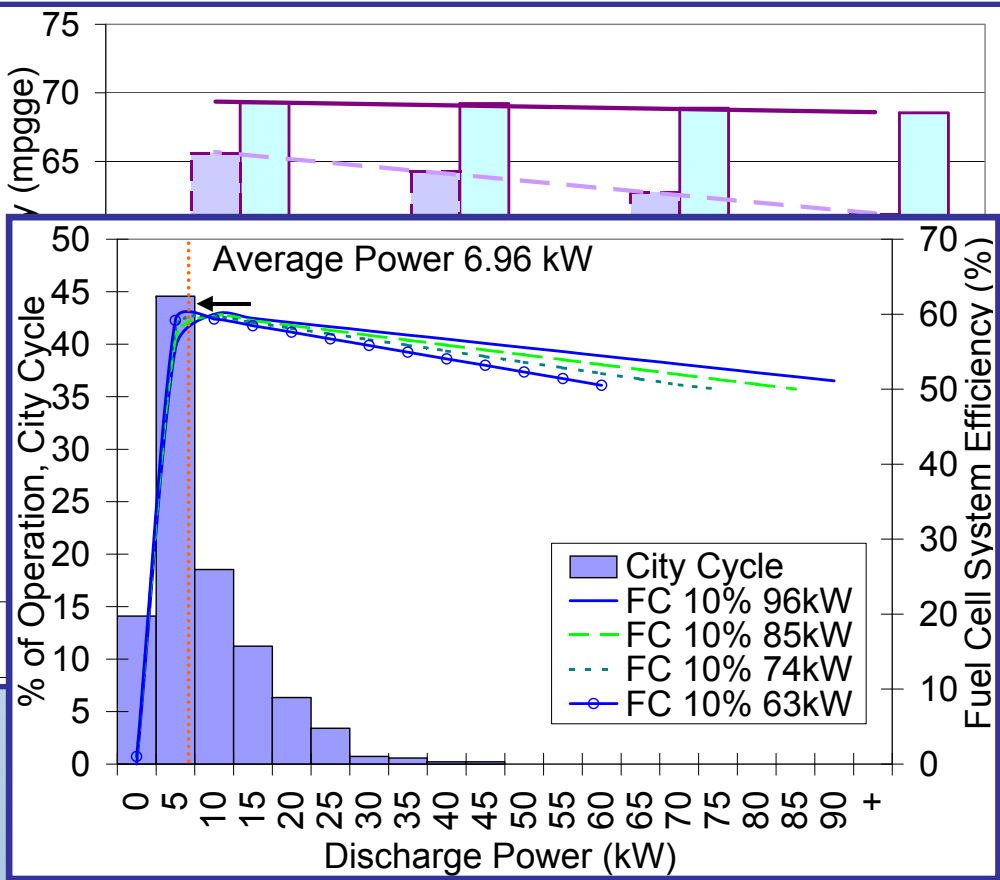
- Investigate the degree of hybridization benefit from:
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# The Benefit of Downsizing the Fuel Cell varies as a function of Peak Efficiency Position



- Downsizing the 10% peak efficiency FC results in the least potential fuel economy improvement  
**≤ 1.0% (combined city/highway) improvement**
- Downsizing the 40% peak efficiency FC results in a moderate to significant potential fuel economy improvement  
**≤ 15.0% (combined city/highway) improvement**

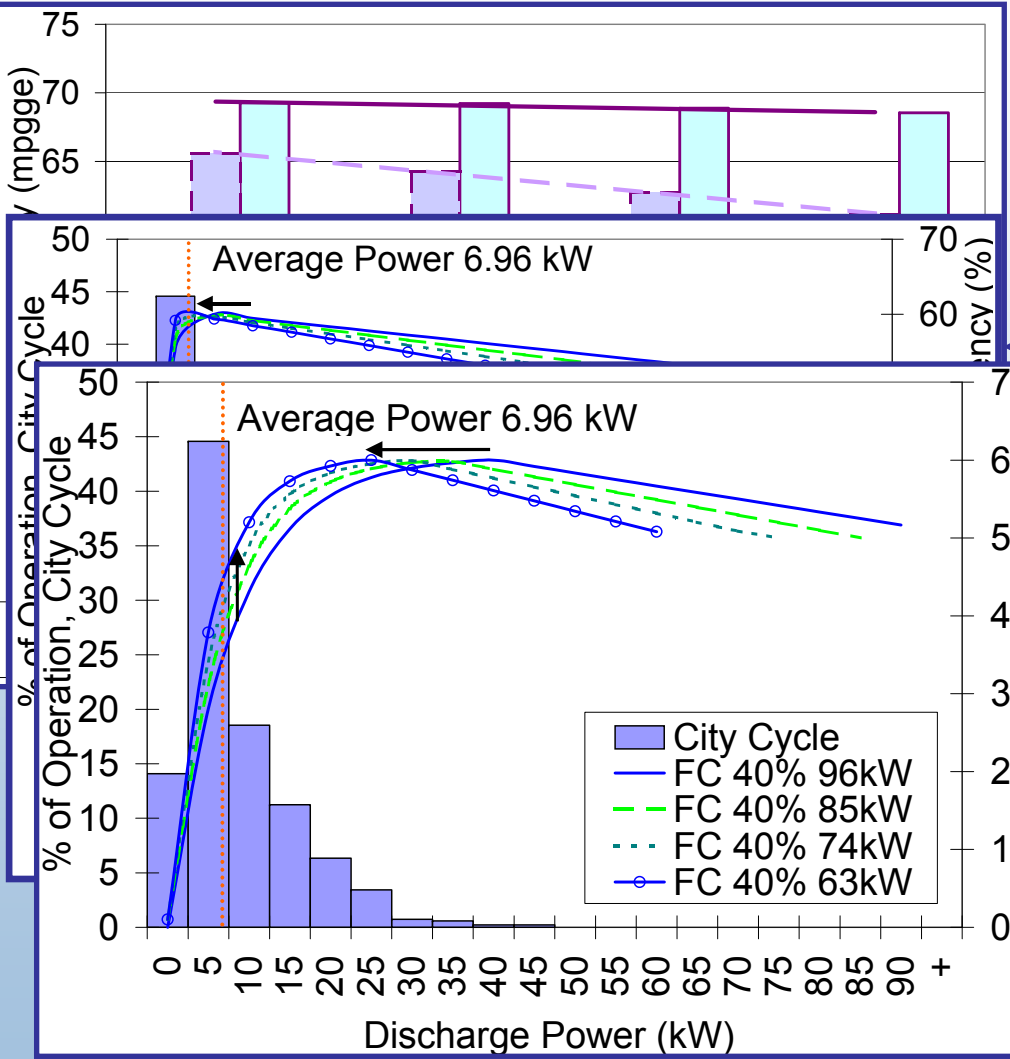
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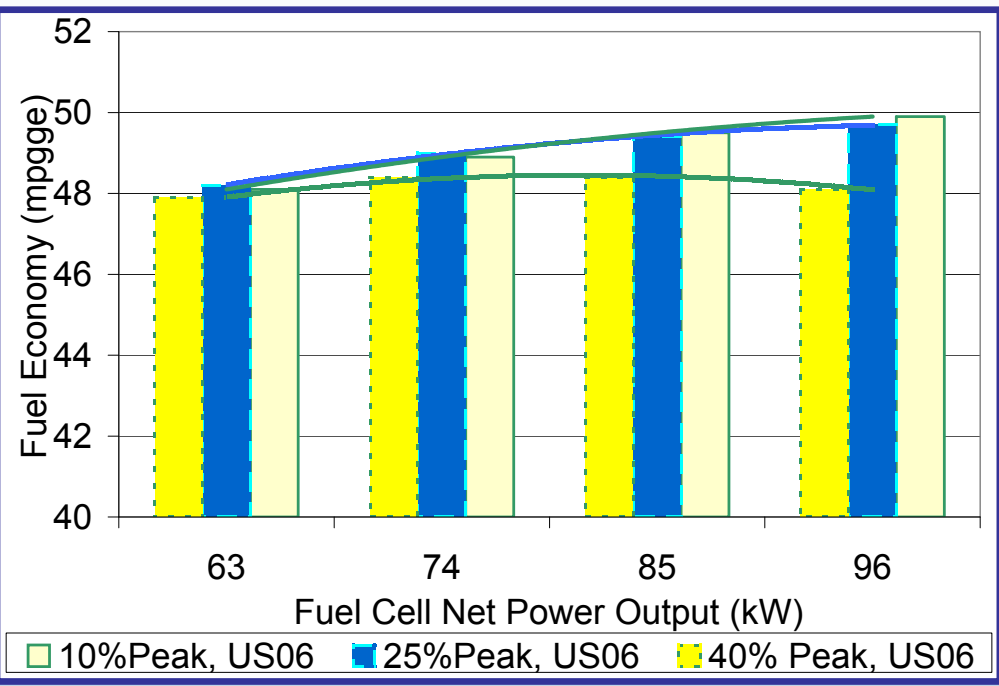
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- Downsizing the 40% peak efficiency FC results in a moderate to significant potential fuel economy improvement  $\leq 15.0\%$  (combined city/highway) improvement

# Downsizing the Fuel Cell Can Have a Negative Affect on the US06 Cycle Fuel Economy



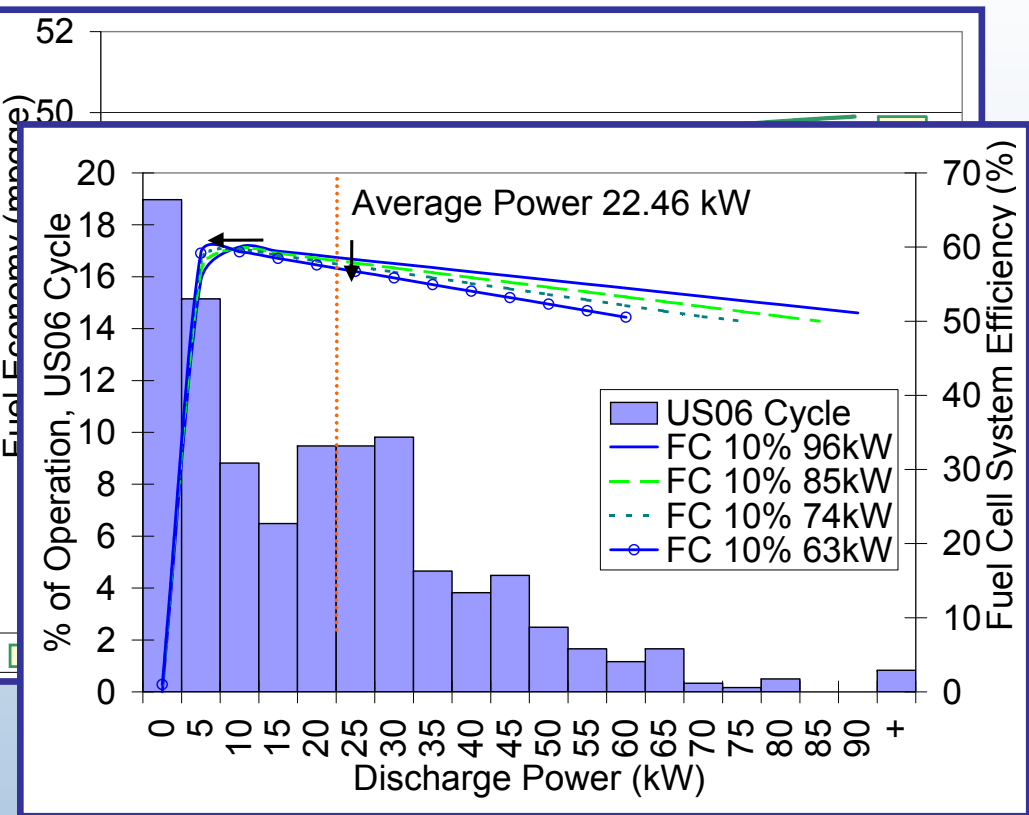
- Downsizing the 10% & 25% peak efficiency FCs results in up to...

**2 mpg less fuel economy**

- Downsizing the 40% peak efficiency FC results in...

**fairly even fuel economy**

# Downsizing the Fuel Cell Can Have a Negative Affect on the US06 Cycle Fuel Economy



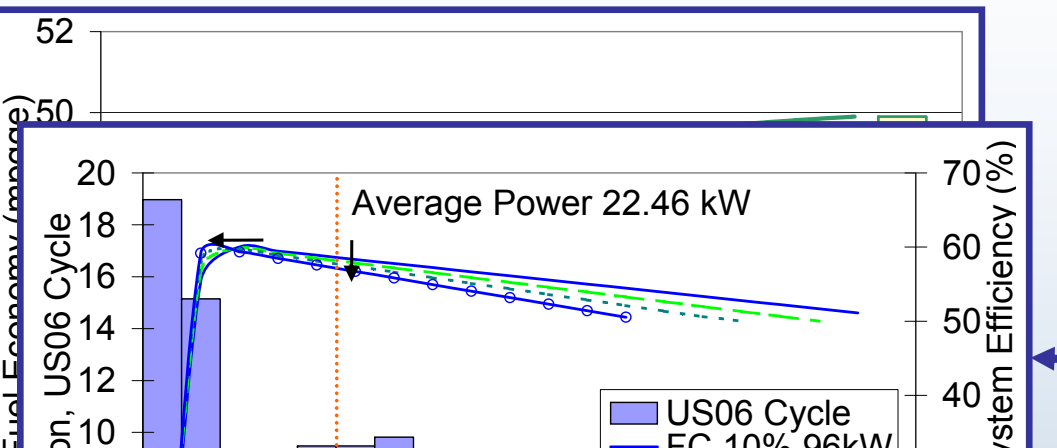
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← **2 mpg less fuel economy**

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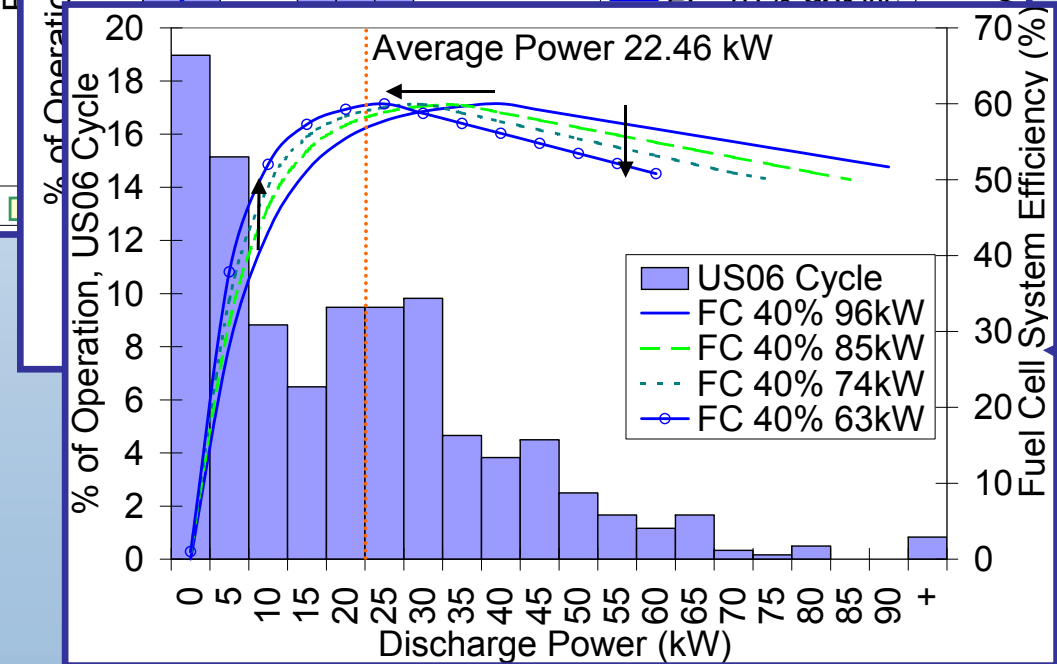
**fairly even fuel economy**

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- Downsizing the 10% & 25% peak efficiency FCs results in up to...

**2 mpg less fuel economy**



- Downsizing the 40% peak efficiency FC results in...

**fairly even fuel economy**

# Objectives

- Investigate the degree of hybridization benefit from:
  - (A) Fuel cell efficiency characteristics
  - (B) Fuel cell downsizing
  - (C) Displacing fuel cell tasks with the ES functionality**
  - (D) Energy recovery through regenerative braking**

# Energy Storage Requirements for Supplementing a Full-Size FC's Limitations

96 kW Fuel Cell	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P <sub>req'd</sub> (kW)	E <sub>req'd</sub> (kWh)	P <sub>regen</sub> (kW)	E <sub>regen</sub> (kWh)
Today's Performance	60	3	61.80	0.2206	-46.49	-0.7332
	60	1	61.80	0.2206	-48.05	-0.7332
	15	3	55.90	0.0580	-46.49	-0.8237
2010 Target	15	1	55.90	0.0580	-48.05	-0.8237
	0	3	48.86	0.0067	-46.49	-0.8265
"Ideal" 96 kW Case	0	1	0.00	0.0000	-48.05	-0.8265

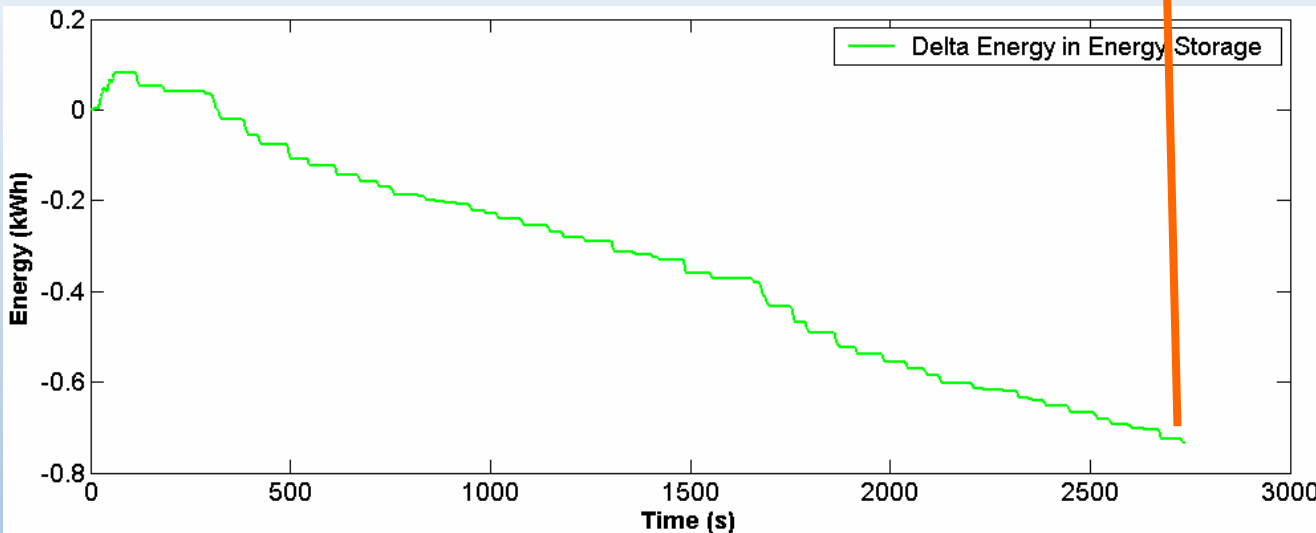
- Similar to stated Honda FCX4 ESS roles.
- Warm-up and ramp rate ESS roles require relatively little energy.

- 2010 Target performance needs fairly similar power, but much less assist energy.

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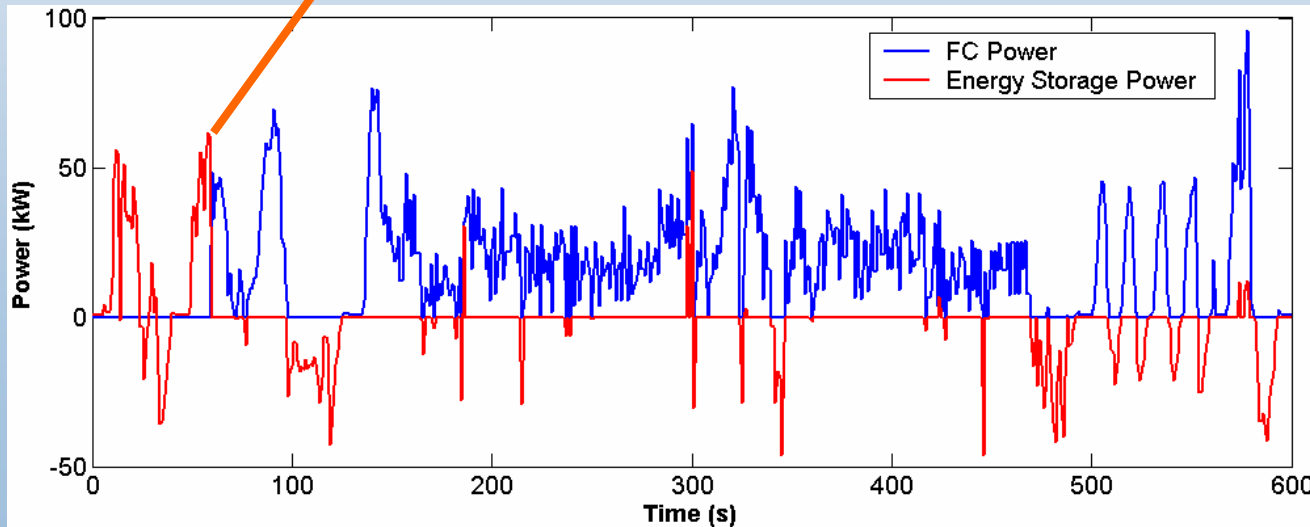
- Similar to stated Honda FCX4 ESS roles.
- Warm-up and ramp rate ESS roles require relatively little energy.
- Big Potential for more active ESS contributions.



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96 kW Fuel Cell	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P <sub>req'd</sub> (kW)	E <sub>req'd</sub> (kWh)	P <sub>regen</sub> (kW)	E <sub>regen</sub> (kWh)
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- Similar to stated Honda FCX4 ESS roles.
- Warm-up and ramp rate ESS roles require relatively little energy.





# Energy Storage Requirements for Supplementing a Downsized FC's Limitations

85 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P <sub>req'd</sub> (kW)	E <sub>req'd</sub> (kWh)
Today's Performance	85	60	3	61.80	0.2206
	85	60	1	61.80	0.2206
	85	15	3	55.90	0.0580
2010 Target	85	15	1	55.90	0.0580
	85	0	3	52.53	0.0333
"Ideal" 85 kW Case	85	0	1	28.67	0.0243

74 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P <sub>req'd</sub> (kW)	E <sub>req'd</sub> (kWh)
Today's Performance	74	60	3	61.80	0.2206
	74	60	1	61.80	0.2206
	74	15	3	56.20	0.0611
2010 Target	74	15	1	55.90	0.0580
	74	0	3	56.20	0.0611
"Ideal" 74 kW Case	74	0	1	39.67	0.0499

63 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P <sub>req'd</sub> (kW)	E <sub>req'd</sub> (kWh)
Today's Performance	63	60	3	61.80	0.2206
	63	60	1	61.80	0.2206
	63	15	3	59.90	0.0889
2010 Target	63	15	1	55.90	0.0766
	63	0	3	59.90	0.0889
"Ideal" 63 kW Case	63	0	1	50.70	0.0766

- With FC downsized, ESS must also assist during max acceleration event.
- ESS is the same as a full-sized FC requires for "Today's" fuel cell performance.

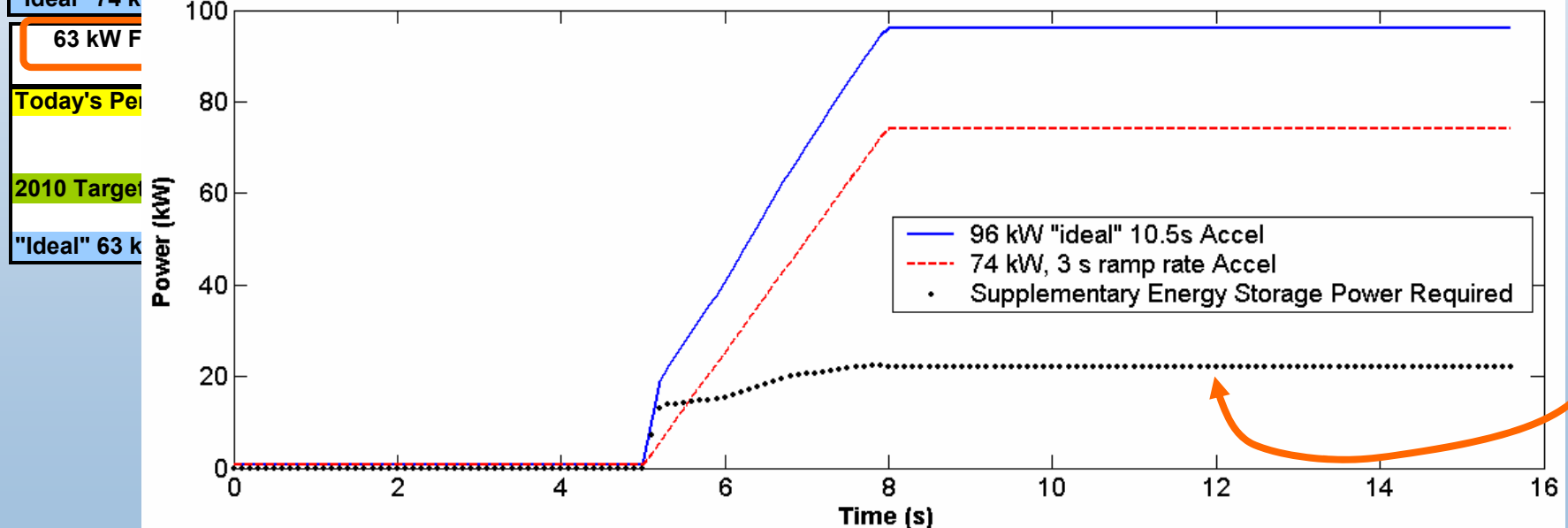
# Energy Storage Requirements for Supplementing a Downsized FC's Limitations

85 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P <sub>req'd</sub> (kW)	E <sub>req'd</sub> (kWh)
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	85	60	1	61.80	0.2206
	85	15	3	55.90	0.0580
2010 Target	85	15	1	55.90	0.0580
	85	0	3	52.53	0.0333
"Ideal" 85 kW Case	85	0	1	28.67	0.0243

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# Energy Storage Requirements for Supplementing a Downsized FC's Limitations

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"Ideal" 85 kW Case	85	0	1	28.67	0.0243

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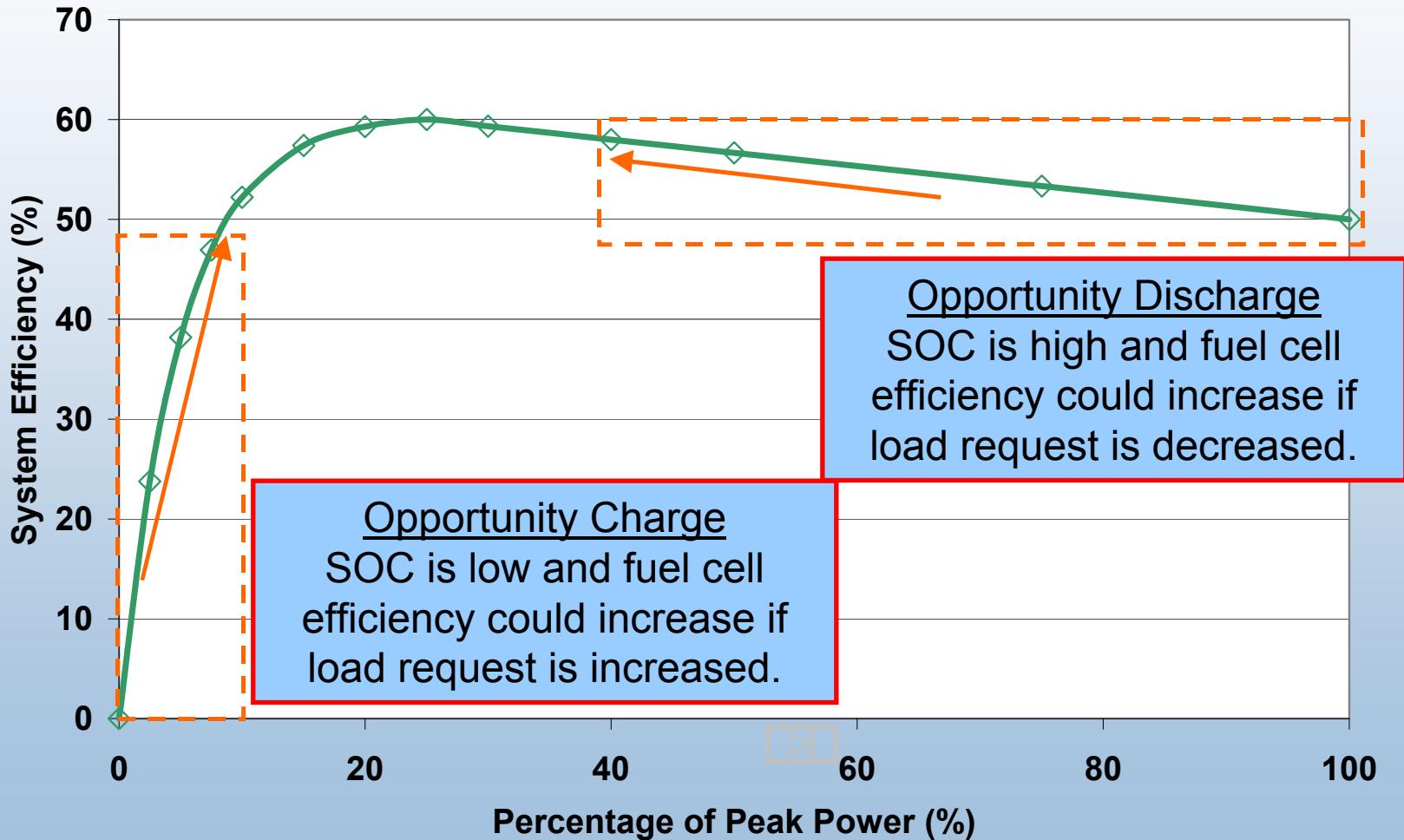
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2010 Target	63	15	1	55.90	0.0766
	63	0	3	59.90	0.0889
"Ideal" 63 kW Case	63	0	1	50.70	0.0766

- With FC downsized, ESS must also assist during max acceleration event.
- ESS is the same as a full-sized FC requires for "Today's" fuel cell performance.
- ESS is nearly the same as a full-sized FC requires for "2010 Target" fuel cell performance.

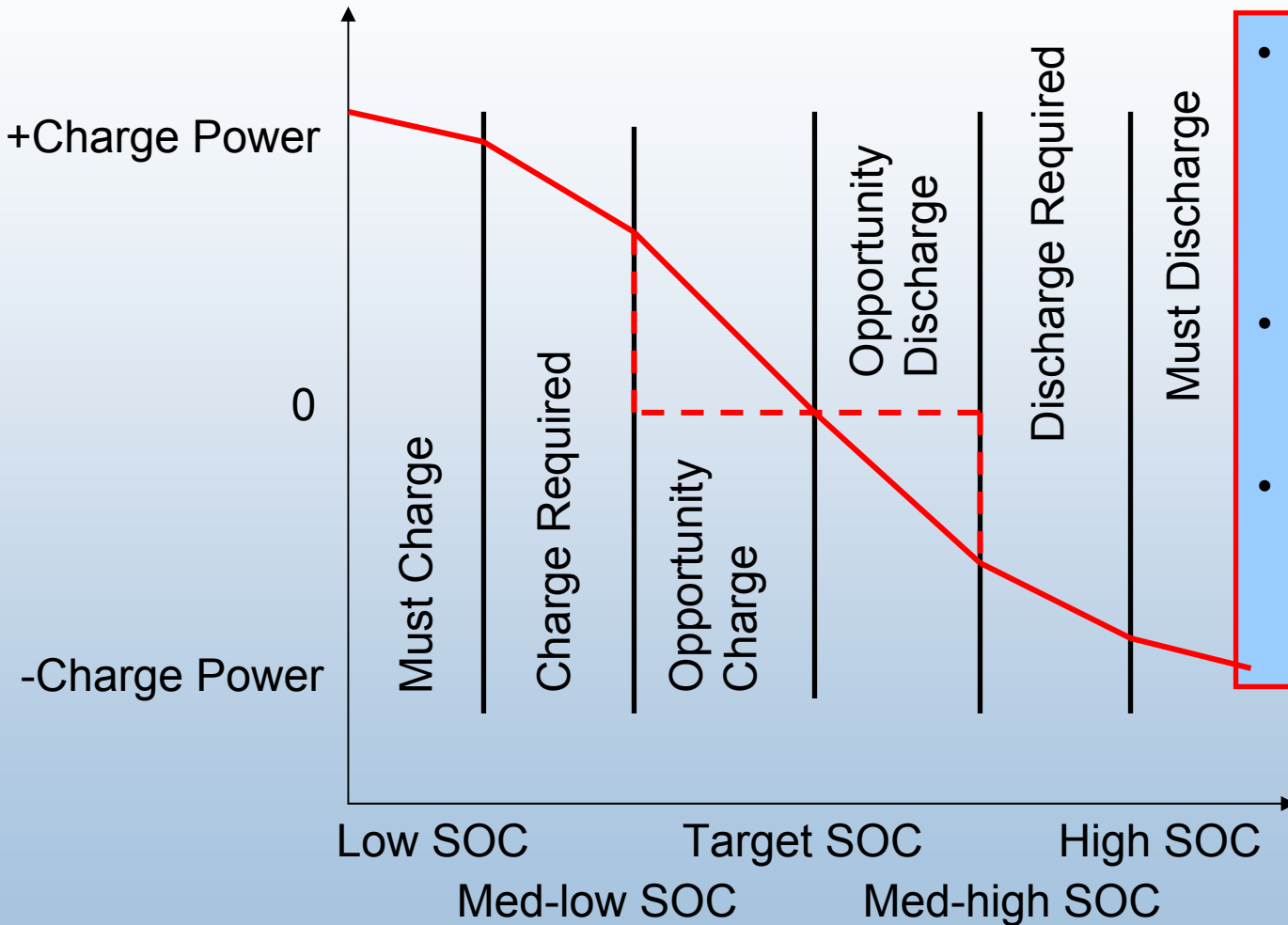
- Therefore, downsizing provides improvement in fuel economy, fuel cell costs, and [in minimal control case] has little to no affect on ESS sizing.

# Current Work - Potential Active Roles for Supplementing Fuel Cell Operation

Curve 2 - Peak Efficiency @ 25% Full Power



# Current Work - Multi-region “Spring” SOC Maintenance Algorithm



- Opportunity region
  - only take action if it makes the prime power plant more efficient
- Could assume different charging rates in each region
- Number of parameters makes it harder to optimize and understand impacts

$$F_c\_pwr\_r = dl\_pwr\_r + charge\_pwr$$

# Summary

- The best fuel economy occurs when peak FC efficiency  $\cong$  typical power operating point (cycle dependant).
- There is positive benefit of downsizing the FC if the peak efficiency is shifted toward the typical power operating point (cycle dependant).
- ES requirements for supplementing FC limitations are suitable for Ultracapacitors or High Power Batteries.
- Downsizing a FC (toward the gradeability limit) with today's or 2010 projected characteristics, Does NOT significantly affect ES requirements (with minimal ES control case).
- There is significant potential for more actively using the ES to manage the FC operation points because of un-used regenerative energy capture.

# Acknowledgements

- ADVISOR™ is used to simulate the fuel cell and energy storage system demands under drive cycle and performance tests.
- This work supports the FreedomCAR Energy Storage technical team in defining energy storage requirements for fuel cell vehicles.